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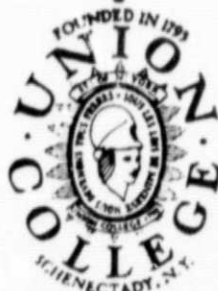
Interim Technical Progress Report

1 February to 31 July 1975

NASA Grant No. NGR 33-032-004

Title: Design and Analysis of Optically
Pumped Submillimeter Waveguide
Maser Amplifiers and Oscillators

Principal Investigator

Thomas A. Galantowicz

Associate Professor of Electrical Engineering

Prepared for

National Aeronautics and Space Administration

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I. INTRODUCTION

This report describes the design and experimental measurements of an optically pumped far-infrared (FIR) waveguide maser and preliminary measurements on a FIR waveguide amplifier. The FIR maser was found to operate satisfactorily in a chopped cw mode using either methanol (CH_3OH) or acetonitrile (CH_3CN) as the active molecule. Two other gases, difluoroethane and difluoroethylene, produced an unstable output with high threshold and low output power when operated in the chopped cw mode. Experimental measurements include FIR output versus cavity length, output beam pattern, output power versus pressure and input power. The FIR output was the input to an amplifier which was constructed similar to the oscillator. An increase of 10% in output power was noted on the 118.8μm line of methanol. Further investigation is in progress in this area.

Section II details the construction of the FIR maser, the method of cavity length tuning, and the design of the cavity. The experimental setup and measurement apparatus are described in Section III. The results of measurements made on the oscillator are described in Section IV. Section V outlines progress made in design and testing of the FIR amplifier.

II. FIR OSCILLATOR DESIGN

A double ended configuration was chosen with the pump radiation coupled into one end of the cavity and the FIR signal coupled out the opposite end. This arrangement simplifies cavity alignment, reduces difficulties of coupling to an amplifier and enables the cavity to be used as an absorption cell to study absorption efficiency of the pump trasition. The cost of double ended versus single ended operation is somewhat higher threshold pump power and FIR signal leaking out the pump input coupling hole. Neither of these effects proves particularly bothersome for the high gain lasing transitions employed. The maser cavity, as shown in Figure 1 consists of a gold coated metal mirror with either a 1.5 or 2 mm hole for pump input coupling and a gold coated Pyrex output mirror with a 15° tapered hole with 1.5 mm opening. The waveguide walls

PUMP INPUT
COUPLING
MIRROR

WAVEGUIDE
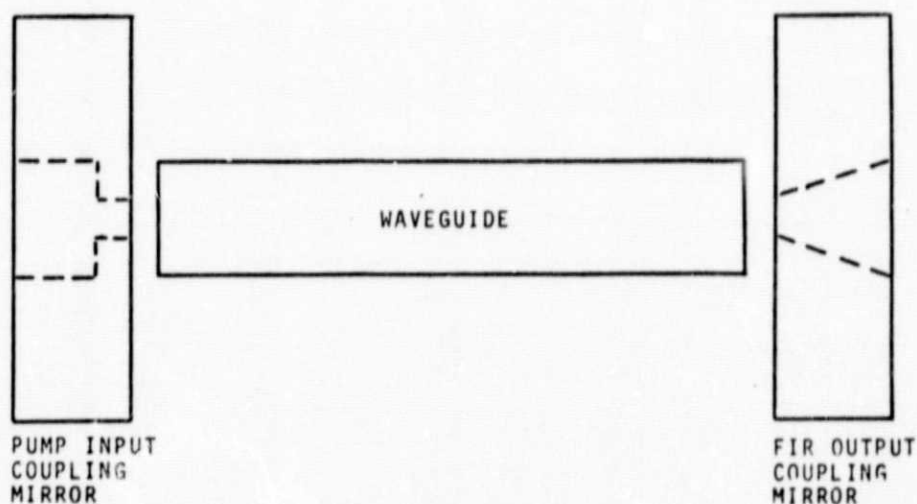
FIR OUTPUT
COUPLING
MIRROR

Fig. 1 Oscillator waveguide cavity configuration

can be metal or dielectric with up to a 1 cm i.d. To date, however, all experiments have been conducted with an 8 mm i.d. copper tube. The Pyrex output mirror has a fixed separation of about 1 mm from the guide and this assembly can be translated axially with respect to the metal input coupling mirror.

The FIR cavity is housed in a 5.1 cm o.d. stainless steel vacuum jacket which is connected by brass bellows to mirror mounts at each end, as seen in Figure 2. The left mirror mount which holds the pump input coupling mirror does not translate. Pump radiation reaches the mirror after passing through a ZnSe window mounted at Brewster's angle. The mirror mount on the right holds the FIR output mirror and is attached to a translation stage allowing cavity length tuning over more than a centimeter. The FIR output mirror assembly shown in Figure 3 employs a z-cut quartz window to complete a vacuum seal.
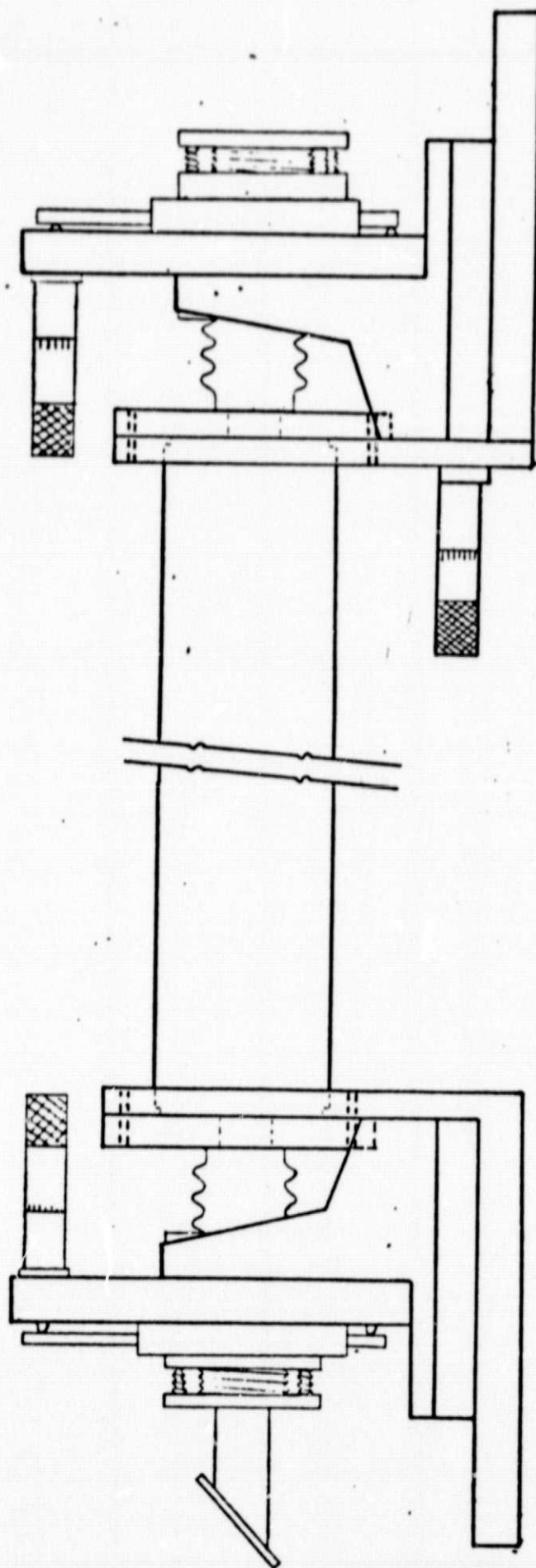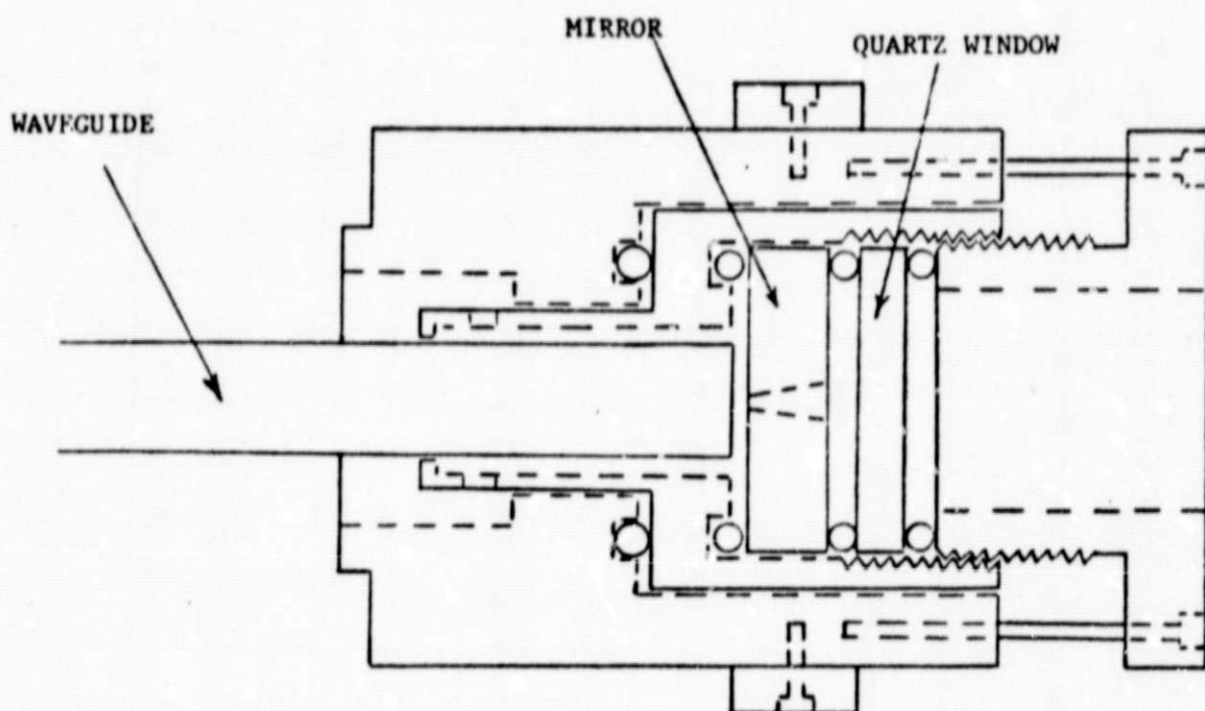
Fig. 2 FIR oscillator

- 4 -

WAVEGUIDE

MIRROR

QUARTZ WINDOW

Fig. 3 FIR output mirror assembly

III. EXPERIMENTAL ARRANGEMENT

Evaluation of the oscillator was conducted using the experimental arrangement shown in Figure 4. The pump source is a Molectron C-250 CO_2 laser with grating tuning and a piezoelectric translator to permit continuous tuning over a single line. Pump power is greater than 10 watts on more than 80 lines from 9.17 to 10.91 µm and greater than 20 watts on many lines near band centers. The pump radiation is externally chopped at 15 Hz by chopper C with a 50% duty cycle such that when the chopper is "off" the beam is deflected to beamsplitter B which sends part of the signal to a CRL Model 201 power meter (D1) and part to a Jarrel Ash 1/2-meter spectrometer. Thus, average pump power and wavelength is continuously monitored. When the chopper is "open" the beam is reflected from a flat gold mirror M2 and a 1 meter radius mirror M3 which focuses the pump radiation through the FIR input coupling hole. Mirror M3 is mounted in a 3 inch speaker cone which is driven by a 90 Hz sine wave. This method was suggested by Prof. Arthur Schawlow to scramble the phases of any pump radiation reflected back to the CO_2 laser. This reduces the effects of reflected power on pump amplitude and frequency stability. The FIR output is detected by a Golay cell with a 3 mm diamond window and 60° acceptance angle. The Golay output is fed to a lock-in amplifier yielding a dc signal proportional to FIR output. The Golay cell can be moved through an angle of 30° on either side of the oscillator axis to measure an output beam pattern.

- 6 -

Fig. 4 Experimental arrangement for oscillator experiments.
Chopper C; beamsplitter B; mirrors M1, M2, M3;
pump power detectors D1, D2; FIR detector G;
capacitance manometer CM; vacuum pump VP.

- 7 -

Pyroelectric detectors have also been employed to detect FIR output. However, neither a lampblack coated SBN detector supplied by the Harshaw Chemical Company nor a Molectron P3-01 detector responded to readiation at 372 μm while both responded at 118 μm.

At 1 rpm motor drives the micrometer of the translation stage which holds the FIR output mirror enabling cavity length tuning. An analog signal proportional to displacement is obtained from a linear variable differential transducer with a sensitivity of 320 mv/mm.

The FIR vacuum system presently consists of a mechanical rough pump and valving to bleed in gas and close off the cavity. The base pressure of the system is below 1 milli-torr as measured by a capacitance manometer. With the FIR cavity sealed off the leak rate is less than 5 mTorr per hour.

IV. OSCILLATOR EXPERIMENTS

The oscillator cavity was composed of an 8 ± 0.05 mm i.d. copper tube 91.4 mm long inserted between two flat gold-coated end mirrors each with a 1.5 mm coupling hole. The copper tube was cleaned with an 8% HCl solution, rinsed with methanol, and dried with a wad of lint-free absorbent toweling.

Oscillator operation was compared with published results for four gases - methyl alcohol; 1,1 difluoroethane; 1,1 difluoroethylene; and methyl cyanide. The output lines measured are shown in Table I. It should be noted that no exhaustive attempt

Gas	CO_2 Line	Pump λ (μm)	FIR λ (μm)	Pressure (Millitorr)	Ref.
CH_3OH	P(36)	9.6948	118.8	400	1
(methyl alcohol)	P(36)	9.6948	170.6	-	1
	P(16)	9.5198	570.5	200	1
$C_2H_2F_2$	P(12)	10.5131	375.0	300	3
(1,1 difluoroethylene	P(14)	10.5321	410	250	4
	P(14)	10.5321	554.4	120	3
$C_2H_4F_2$	P(20)	10.5910	465	100	4
(1.1 difluoroethane)					
CH_3CN (methyl cyanide)	P(20)	10.5910	372.87	150	2

TABLE I

FIR Maser Output

was made to determine all possible FIR output lines for each
molecule. Since the lines in Table I have all been previously
reported they were used to check the accuracy and sensitivity of
detectors and to get a feel for alignment, tuning and stability
problems. It was found that FIR wavelength measurements agreed
with published values to within $\pm$ 2%. In Table I FIR wavelengths
as reported in the literature have been recorded where these
measurements have greater accuracy. The pressures in Table I
are values for optimum output power. They are not appreciably
different from published values for the open resonator FIR maser.
Pump power coupled into the FIR cavity was less than 5 watts for
CH_3OH and CH_3CN. It was under 15 watts for $C_2H_2F_2$ and $C_2H_4F_2$.
A detailed study of the dependence of FIR output power on pump
power and pressure was undertaken only for CH_3OH.

Methyl alcohol pumped on the P(36) line of the 9.6μm- CO_2 band
produces a wealth of output lines as shown in the cavity length scan
of Figure 5. The line widths are quite narrow corresponding to a

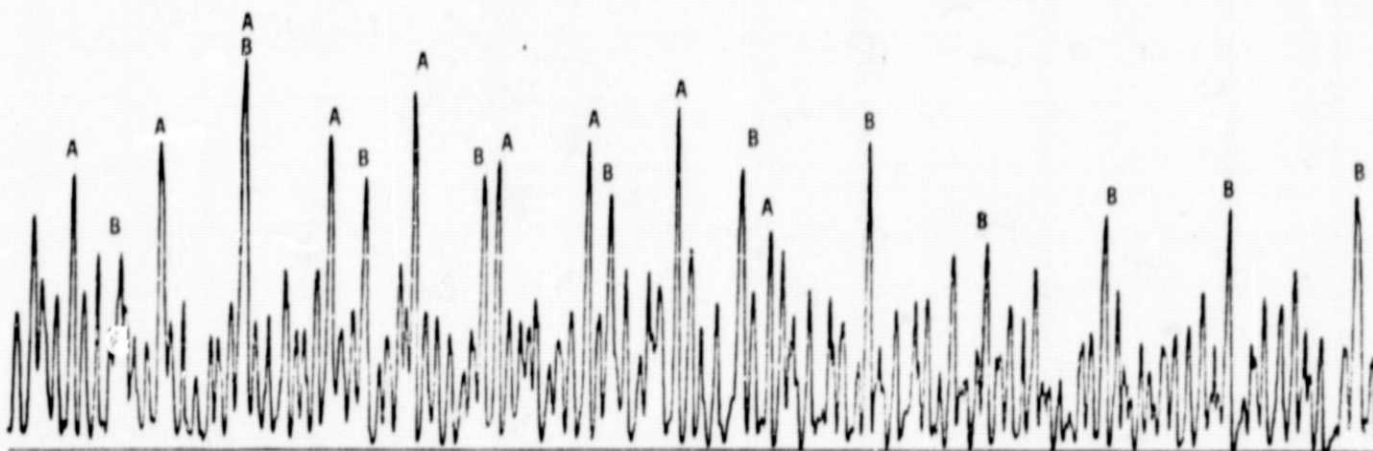Fig. 5 FIR cavity length scan. Lines labeled A correspond
to 118.8 μm transition while lines labeled B
correspond to 170.6 μm transition in CH_3OH pumped
at 9.6948 μm.

change in cavity length of about 5μm between half power points. These lines correspond to several higher order transverse modes and cascade transitions as well as output at 118.8μm (lines labeled A) and at 170.6μm (lines labeled B). The relative amplitudes of the lines can be varied by fine tuning the pump frequency. It was found that one of the cavity mirrors could be rotated an angle of greater than 0.5° from the cavity axis without appreciably affecting the output power at 118.8μm. Also, it was noticed that output power increases as the gap between the copper guide and the end mirrors decreases. This happens because the cavity loss decreases as the discontinuity is reduced.

A study of output power versus pump power and pressure was made for the 118.8μm line of methyl alcohol. Several features characteristic of FIR maser operation are evident in the plot of output power versus pump power at constant pressure given in Figure 6:

a) The maser ascillation threshold increases with pressure as expected, since collisional de-excitation of the upper laser level increases with pressure.

b) At pressures above 100 milliTorr the pump transition is not saturated for pump powers as high as 20 watts (cw power).

c) There exists an optimum operating pressure for a given pump power. At low pressure the gain increases as the molecular density increases. This is eventually offset, however, by pressure broadening and increased collisional depopulation of the upper laser level.
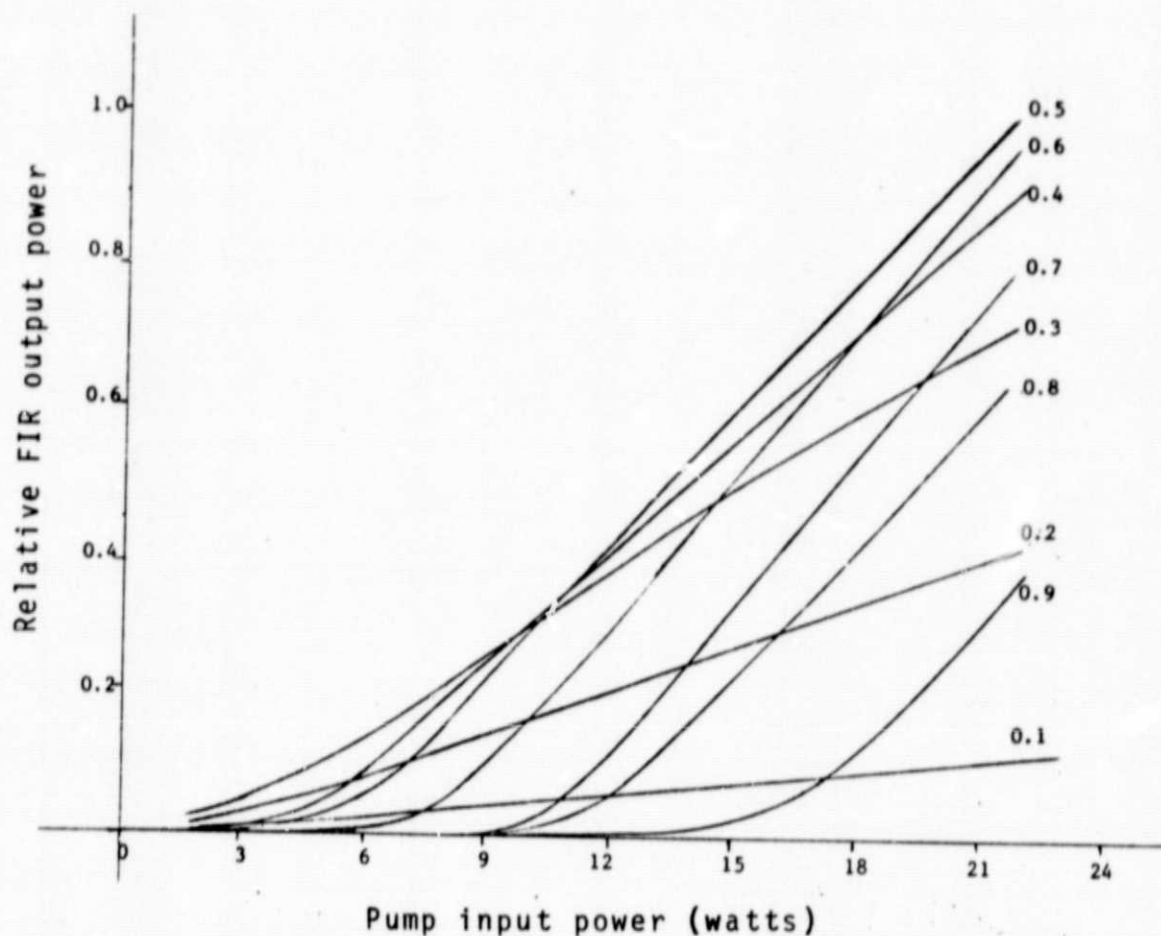
Fig. 6   FIR output power versus pump power at various
         pressures (given in Torr) for the 118.8μm line
         of CH_3OH

d)   The optimum pressure increases with increasing power.
This is evident from the fact that the slopes of the constant
pressure curves increase in Figure 6 as pressure increases up
to 0.7 Torr.   The curves for 0.8 and 0.9 Torr have linear
regions which are too short to make any valid comments.   This

- 12 -

shift in optimum pressure can be seen in Figure 7 which plots output power versus pressure for fixed input power. This curve is plotted from the data of Figure 6. It was noted that the FIR output power is roughly proportional to the fourth power of the optimum pump pressure as stated in Ref. 5.

The maximum output power on the 118.8μm line of methly alcohol was estimated to be 2 milliwatts. FIR output amplitude is approximately proportional to pump amplitude. Although the dependence of FIR output on pump frequency tuning was not accurately measured, it did appear that the pump frequency could be tuned over a range an order of magnitude less than the estimated linewidth of the FIR pump transition.

Methyl cyanide was found to produce a stable outout at 372.87μm with output power comparable to methyl alcohol. FIR output power versus cavity length is shown in Figure 8 for various operating pressures. The horizontal scale in Figure 8 is 2.5 times smaller than that of Figure 5. By comparison, it can be seen that there are fewer lines and the linewidth is wider for methyl cyanide than for methyl alcohol. This is made obvious on the expanded scale of Figure 9 which is the same scale as Figure 5. The lines are wider because of the factor of 3 increase in wavelength. Note also that the strong peaks at 372μm have a fine structure composed of higher order transverse cavity modes. The beam patterns were studied for two of these fine structure peaks resulting in the beam patterns of Figure 10 confirming that the peaks correspond to different transverse modes.
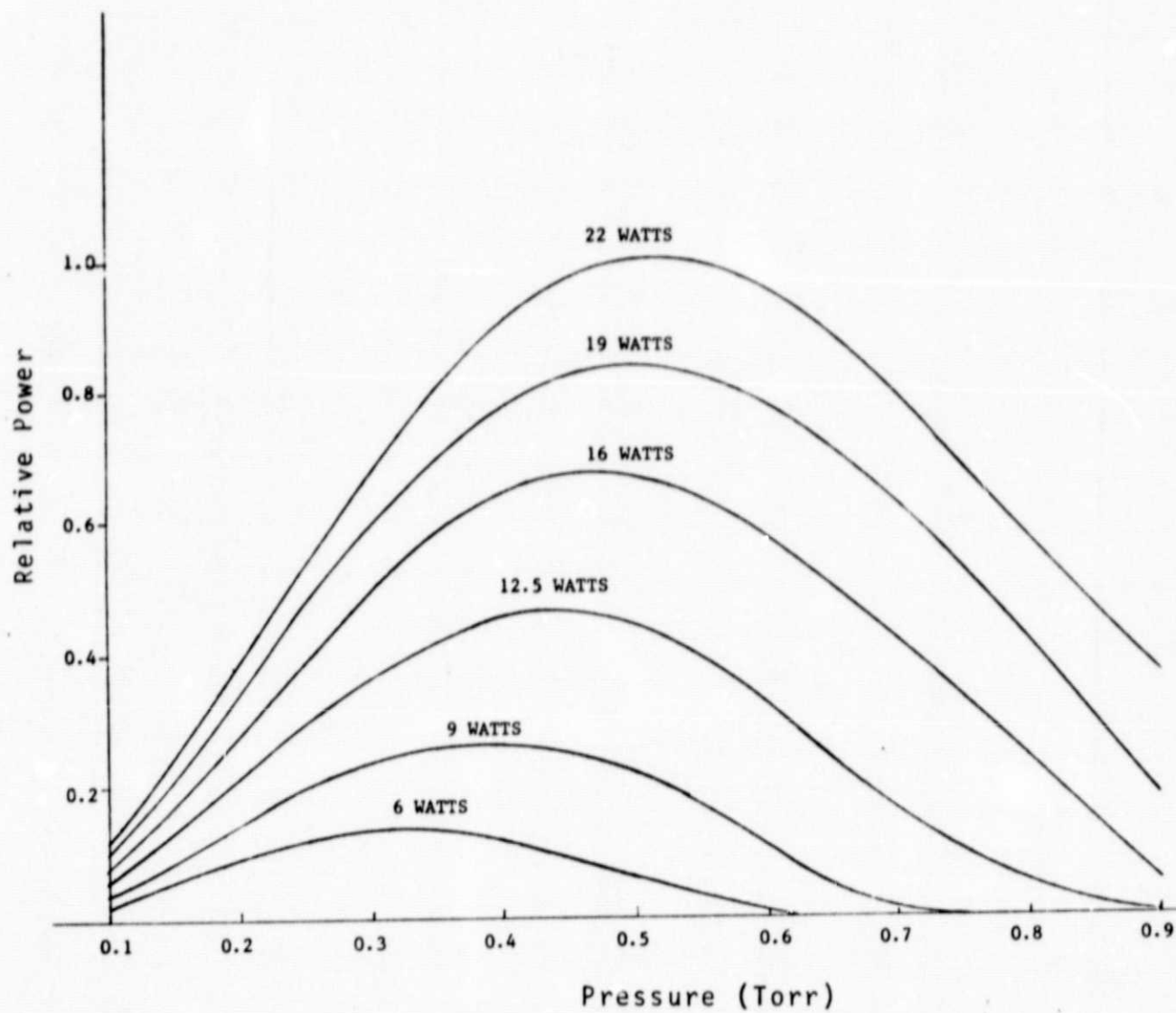
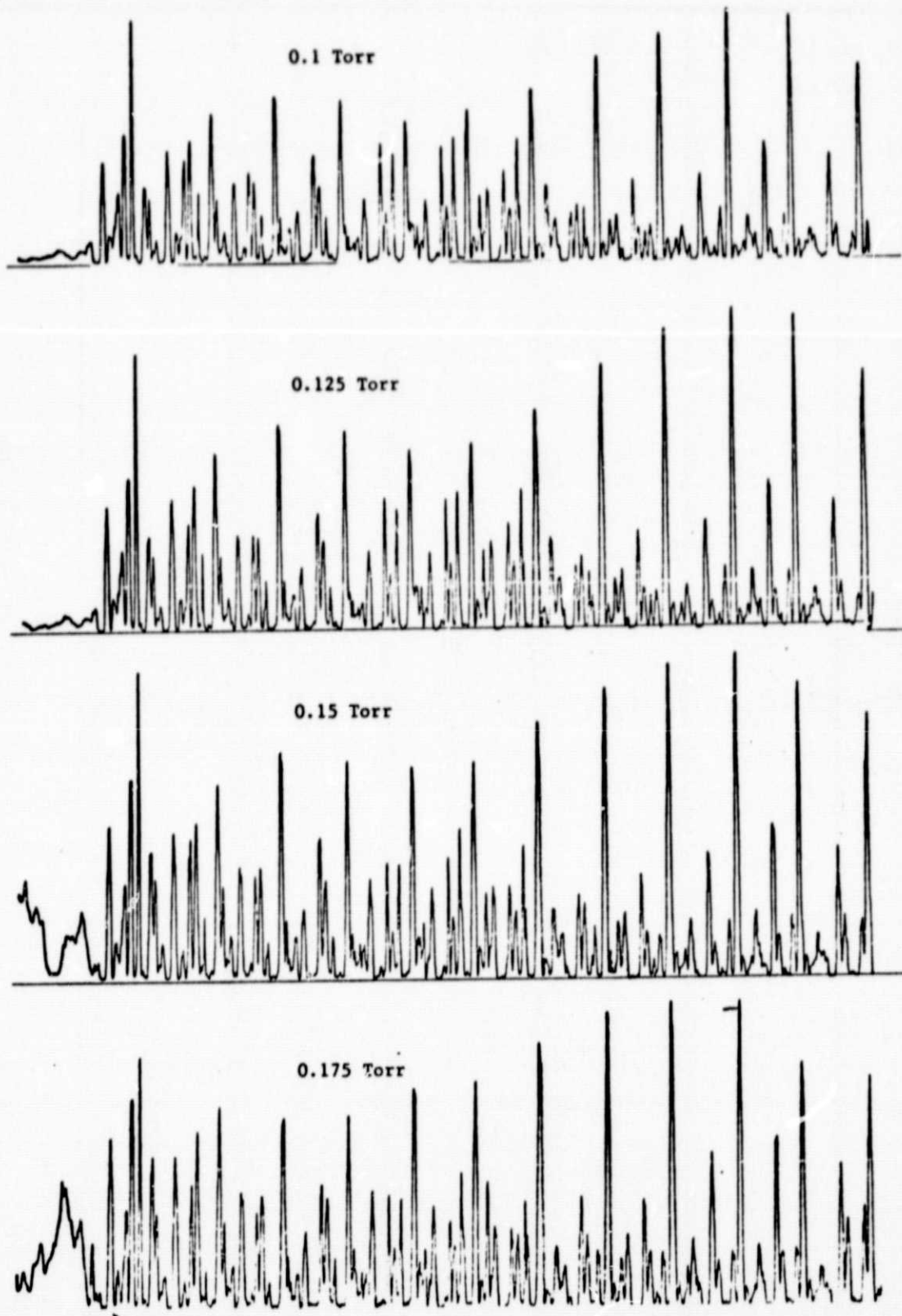Fig. 7   FIR output power versus pressure for 118.8μm
line of CH_3OH

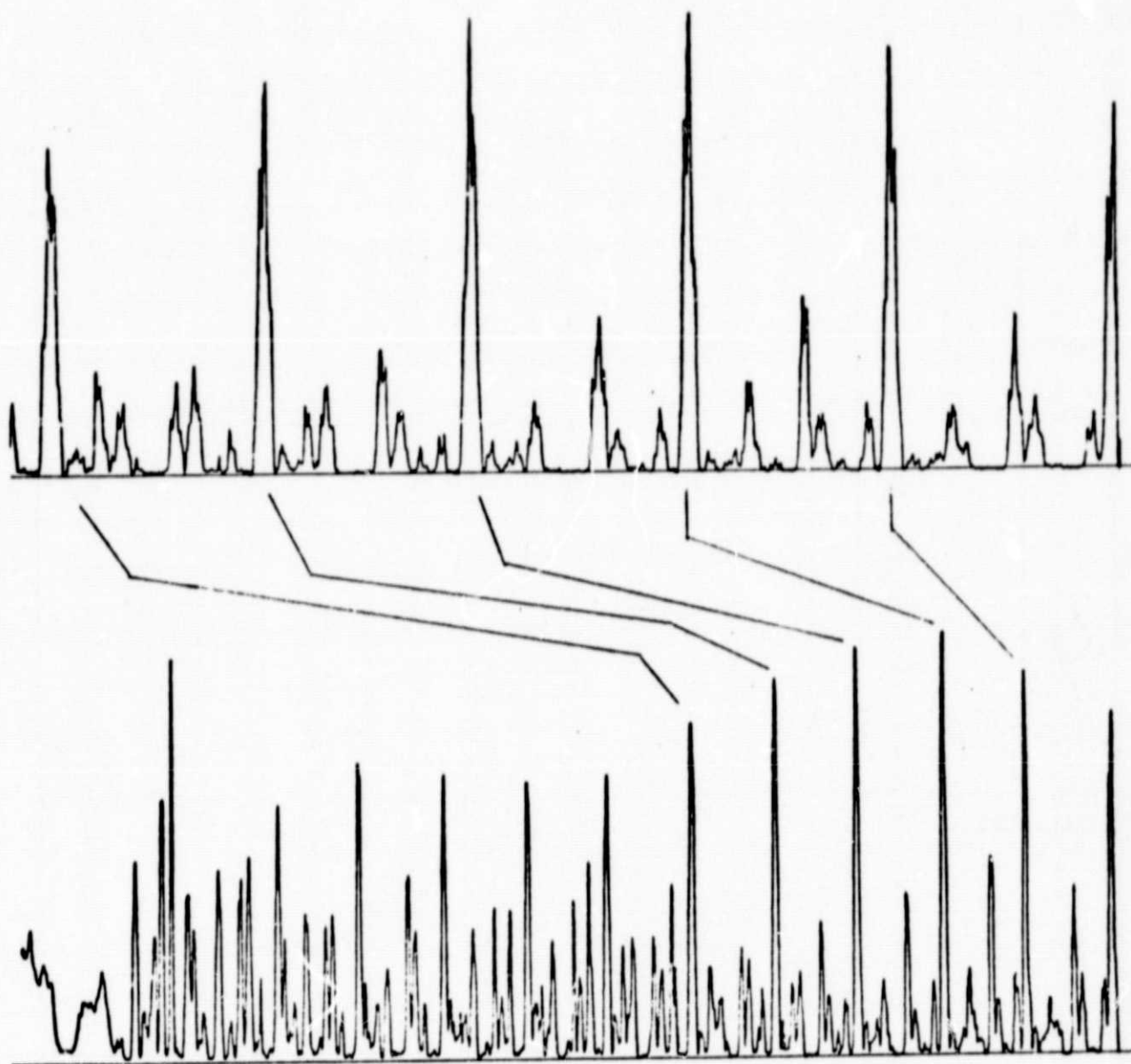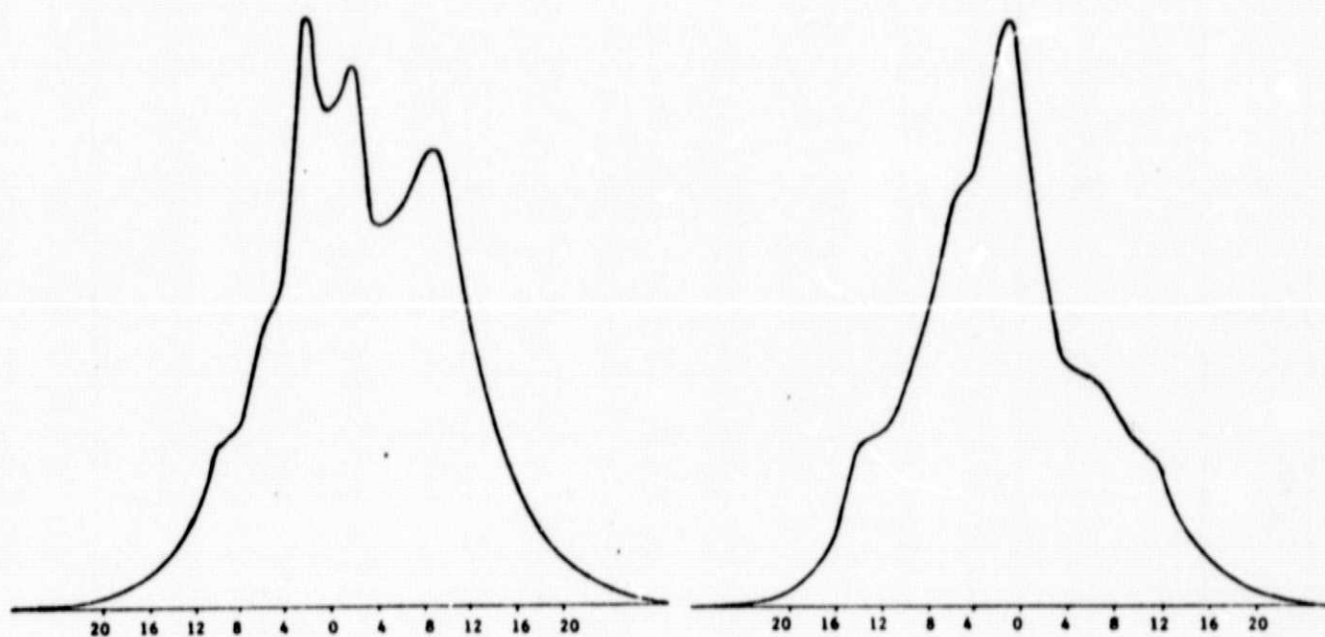Fig. 8 Cavity length scans at various pressures for
CH$_3$CN pumped at 10.5910μm.

Fig. 9 Expanded scale (2.5X) of cavity length scan for
CH$_3$CN pumped at 10.5910μm.

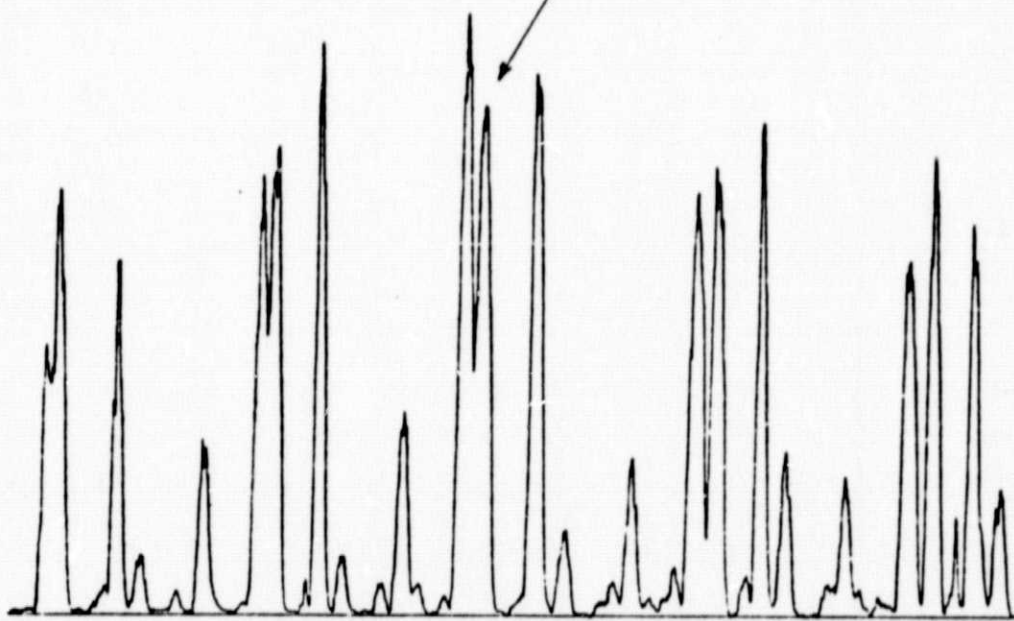Beam angle (in degrees)

Beam angie (in degrees)

Fig. 10 FIR output beam patterns for two output lines.

A further characteristic of the curves of Figure 8 is the broad peak at the end of the scan where the end mirrors are closest to the copper guide. This peak is not repeatable and does not seem to depend on pressure. On occasion the power output within this peak is much higher than any other line. The reason for this is not clear but it is thought to be related to one mirror making physical contact with the guide and changing both the cavity Q and the mirror alignment.

Oscillator operation was obtained at 465μm using difluoroethane ($C_2H_2F_2$) with a pump power of about 10 watts. The output lines are quite narrow and very sparse indicating that the maser was barely operating above thrshold.

Measurements of oscillator operation with difluoroethylene ($C_2H_2F_2$) yielded output lines at 3 different wavelengths (see Table I) with a pump power of about 10 watts. Several smaller peaks were noted indicating higher order modes were present. The FIR linewidth was narrower than for methyl alcohol.

V. FIR AMPLIFIER

The FIR oscillator output was the input signal to an amplifier which consisted of an $8^{\pm}.05$mm i.d., 91.4mm long copper tube contained in a 5.1 cm o.d. stainless steel vacuum jacket through a ZnSe Brewster window at one end of the tube while the FIR signal entered the opposite end of the tube through either a ZnSe or Quartz window. In operation both the oscillator and laser were maintained at the same pressure.

The experimental arrangement for amplifier studies is shown in Figure 11. The CO_2 pump beam is split by a 50% germanium beamsplitter B into two beams, one which is focused into the oscillator and another which is focused into the amplifier. The FIR output from the oscillator is collimated by a polyethylene lens L and reflected by mirror M1 into the amplifier - M1 and M2 are flat aluminum mirrors with center holes to pass the narrow pump beam while reflecting the wider FIR beam. The Golay cell D detects the FIR signal which has passed through the amplifier and reflected off M2. In front of the Golay cell is a polyethylene lens and quartz crystal flat to filter out any stray 10.6 μm radiation and focus the FIR beam.

Amplifier operation was investigated using CH_3CN as the active gas. Signal gain was determined by measuring the FIR signal power before and after blocking the CO_2 pump beam for the amplifier. In this manner a signal gain of about 10% was measured with the amplifier. This single pass gain appears to be limited by low absorption
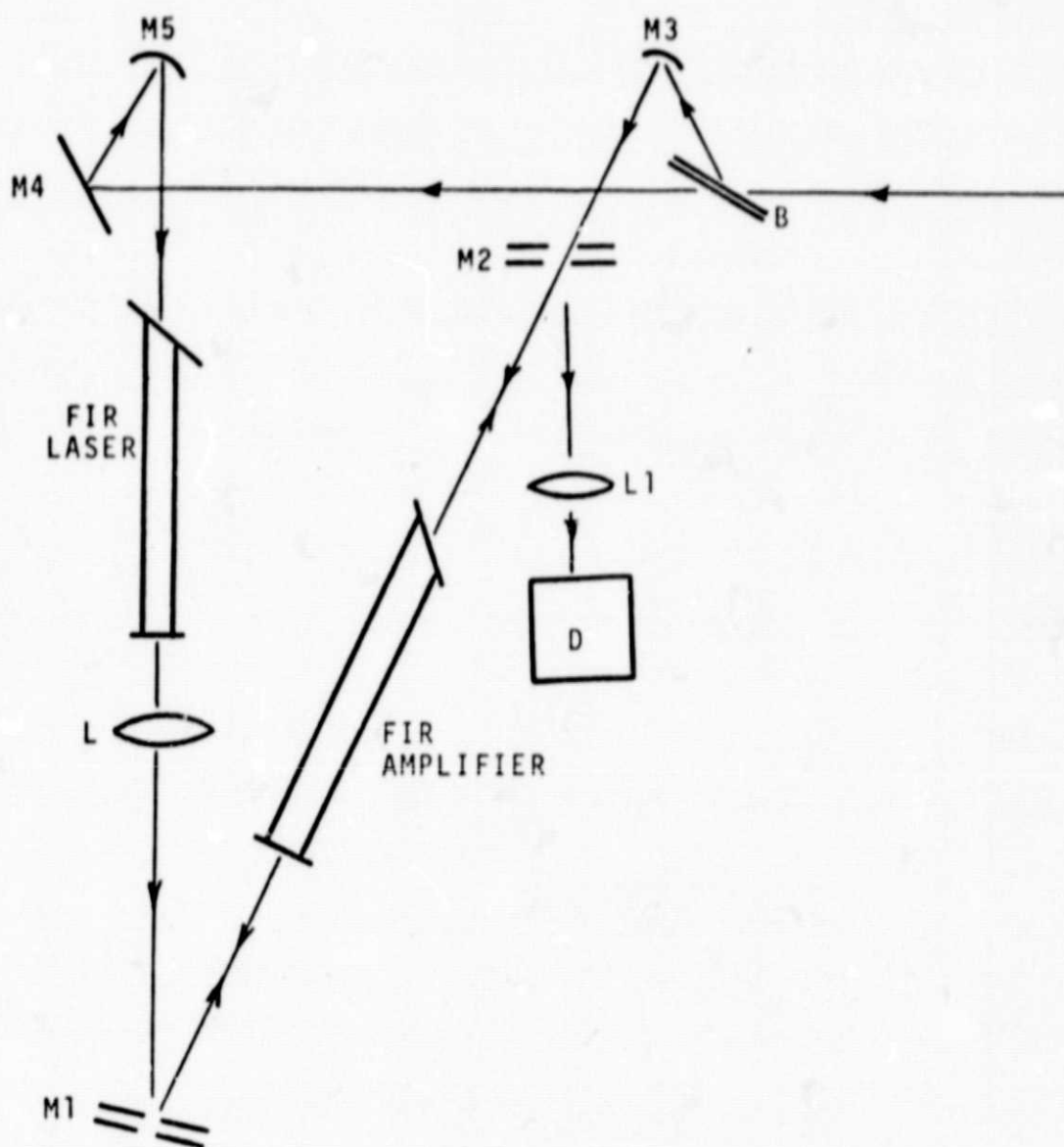
Fig. 11 Experimental arrangement for oscillator
experiments. Beamsplitter B; mirrors M1
through M5; lenses L and L1, FIR detector D.

of the pump beam by the gas in the amplifier. An attempt was
made to insert reflective rings at the ends of the copper tube
in the amplifier to cause the pump beam to reflect more in-
side the cavity. Negligible improvement was noted. Work is
in progress to improve pump beam absorption and measure small
signal gain and saturation.

VI. ANTICIPATED EXPERIMENTS

a) <u>Oscillator</u>: The oscillator cavity configuration will be improved by using a piston mirror inside the copper tube at the pump input end. This should reduce the cavity discontinuity and maintain a nearly constant discontinuity as cavity length is scanned. In addition an attempt will be made to obtain a hybrid output mirror similar to that described in Ref. 6 for use as a FIR output mirror. This should result in improved output beam mode quality and lower threshold.

The oscillator output is sensitive to pump amplitude and frequency stability and oscillator cavity length stability. Of these three pump frequency stability seems to be the most critical. Improved frequency control will be obtained by temperature control of the water coolant for the CO_2 laser. Consideration will be given to active stabilization of the pump frequency.

With these improvements accurate measurements of FIR output dependence on pump power and pressure can be made and the cavity oscillation modes of waveguides of various materials and diameters can be studied. From these measurements a realistic model of FIR waveguide maser operation can be formulated.

b) <u>Amplifier</u>. The amplifier cavity configuration will be improved to increase absorption at the pumping transition. Small signal gain and saturation parameter will be studied and regeneration of the FIR signal will be implemented to improve amplifier gain.

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